



Application of Aluminum Foam for Stress-Wave Management in Lightweight Composite Integral Armor

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Abstract

Closed-cell aluminum foam offers a unique combination of properties such as low density, high stiffness, strength, and energy absorption that can be tailored through design of the microstructure. During ballistic impact, the foam exhibits significant nonlinear deformation and stress-wave attenuation. Composite structural armor panels containing closed-cell aluminum foam are impacted with 20-mm fragment-simulating projectiles (FSP). One-dimensional plane strain finite element analysis (FEA) of stress-wave propagation is performed to understand the dynamic response and deformation mechanisms. The FEA results correlate well with the experimental observation that aluminum foam can delay and attenuate stress waves. It is identified that the aluminum foam transmits an insignificant amount of stress pulse before complete densification. The ballistic performance of aluminum foam-based composite integral armor is compared with the base-line integral armor of equivalent areal density by impacting panels with 20-mm FSP. A comparative damage study reveals that the aluminum-foam armor has better and finer ceramic fracture and less volumetric delamination of the composite backing plate as compared to the base line. The aluminum-foam armors also showed less dynamic deflection of the backing plate than the base line. These attributes of the aluminum foam in integral armor system add a new dimension in the design of lightweight armor for the future armored vehicles.

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1. Introduction

The U.S. Army has established and documented requirements for lightweight structural armors that exhibit significant advancements in the integration of ballistic and structural performance [1]. Figure 1 depicts the historical development of armors for 0.50 cal. heavy machine gun threat demonstrating continuous improvements; yet, significant challenges exist in further reducing the areal density by half. Such a reduction in armor weight requires the integration of new materials, improved understanding of stress-wave propagation at dissimilar material interfaces, optimization of multiple competing performance metrics, and innovative armor concepts.

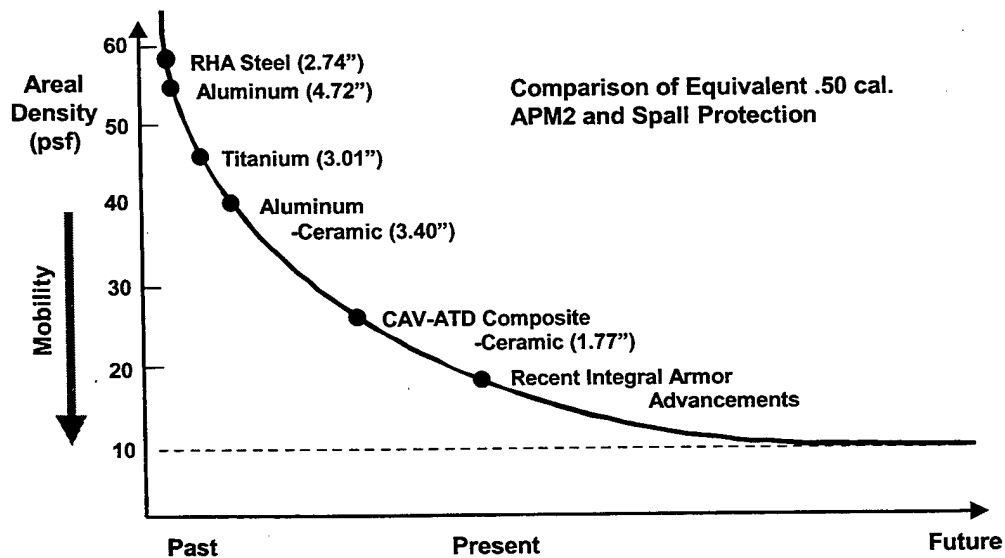


Figure 1. Historical development of composite integral armor.

One successful composite integral armor (CIA) developed by United Defense Limited Partnership (UDLP) for the U.S. Army is a hybrid material system consisting of a ceramic strike face, a thin rubber layer, and an S-2 glass-based composite backing plate (Figure 2) [2]. This armor is required to provide ballistic protection and structural integrity at minimal areal density. Most CIA configurations utilize a rubber layer between the ceramic-tile layer and the composite-backing plate to increase the armor's multihit capability and structural damage tolerance [3, 4]. Experimental evidence shows that an increase in rubber layer thickness decreases the dynamic deflection of the composite backing plate [5]. One-dimensional numerical stress-wave experiments revealed

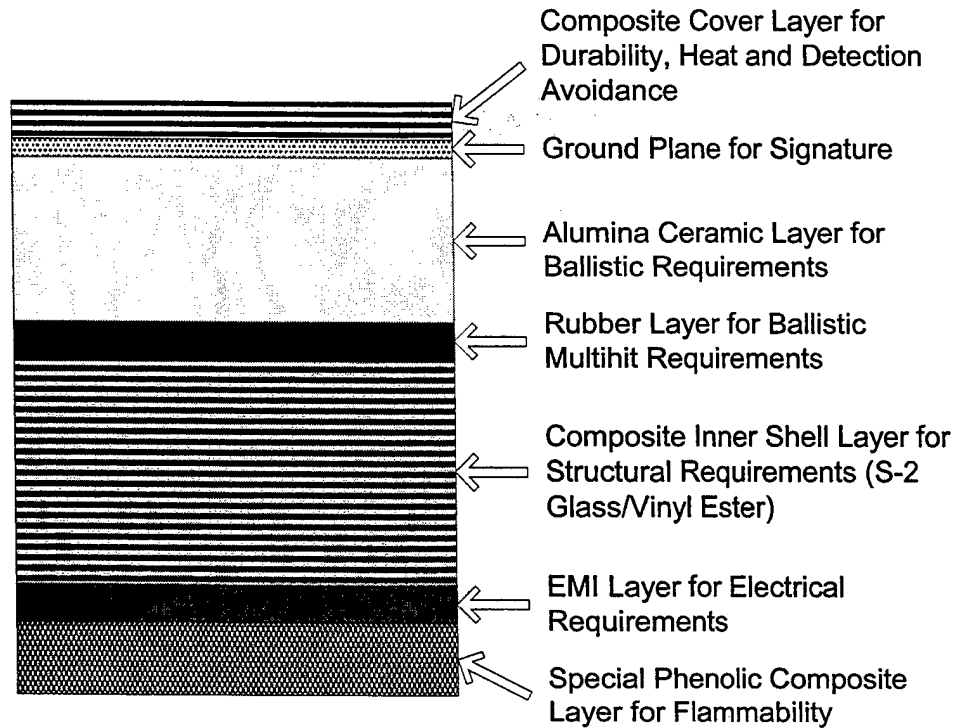


Figure 2. Components of integral armor structure.

that rubber delays the stress wave transfer and reduces the amplitude of transmitted stress wave to the backing plate [5]. The experimental and numerical results point to the importance of managing stress-wave propagation in CIA during ballistic impact. However, rubber is a compliant material and reduces the structural stiffness of the armor. Hence, an optimal rubber-layer thickness that balances the ballistic and structural performance at minimal weight should be determined to meet the specific mission requirements for a vehicle. Closed-cell aluminum foam is an alternative material to the rubber layer that has the potential to improve structural stiffness and ballistic properties. In the present study, we describe the stress-wave experiment through closed-cell aluminum foam, numerical stress-wave propagation models, design concepts, manufacturing and ballistic testing of a new generation of CIA.

2. Closed-Cell Aluminum Foam and Stress Wave Experiment

A variety of foaming processes and properties of closed-cell aluminum foam has been reported in the literature [6-10]. However, the foaming process via a

powder metallurgy route produces a solid skin, which may be of interest especially for the surface bonding of another material, has high specific strength, and unique nonlinear compressive behavior [11]. Figure 3 shows the quasi-static engineering stress-strain behavior of such closed-cell aluminum foam of different densities (gm/cm^3). The flow stress of the foam is a strong function of foam density and the stress-strain curves can be divided into three regions—linear elastic region, collapse region, and densification region. In region 1, the only deformation that occurs is elastic and is due to cell-wall bending. This is followed by region 2 in which plastic collapse of the first cell wall occurs and the stress drops. In region 3, the foam progressively collapses and densifies. It was observed that deformation in region 3 was highly localized and proceeded by the advance of a densification front from deformed to undeformed regions of the sample. It has also been found that such a type of aluminum foams is essentially strain rate independent [11–12]. Hence the quasi-static properties of aluminum foam presented in Figure 3 are used in our numerical simulations.

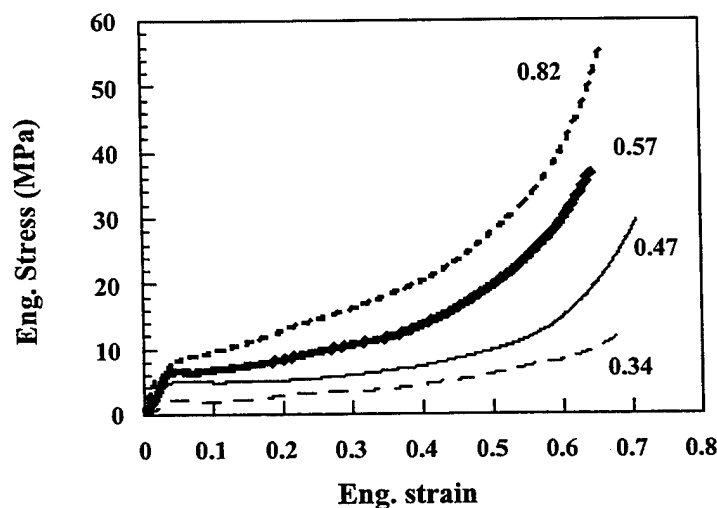


Figure 3. Quasi-static stress-strain behavior of closed-cell aluminum foam. Numbers on the figure represent foam density in gm/cm^3 .

Ballistic targets with and without aluminum foam were designed and tested to compare the shock-wave propagation through the aluminum foam (Figures 4[a] and 4[b]). The target without aluminum foam had an areal-density of $161.03 \text{ kg}/\text{m}^2$ (32.98 psf) and the target with aluminum foam had an areal-density of $157.75 \text{ kg}/\text{m}^2$ (32.31 psf). High hardness steel (HHS), aluminum foam, alumina ceramic (Al_2O_3), and 7,039 aluminum plates are bonded together with a thin layer of fast-setting epoxy adhesive. Piezoresistant stress gages (Dynasen Model

Mn/Cn 4-50-EK) are sandwiched between two ceramic layers to monitor the dynamic stress through the ceramic layer. These gages consist of two separate interlaced 50- Ω foil grids enclosed in a polyamide plastic film. One of the grids is made of manganin and is used to measure stress. The other is made of constantan and is used to measure lateral strain. Both grids are 6.35-mm square and 0.127 mm thick. The measured strain is used to correct the stress measurements. The gages are connected to a Dynasen CK-15-300 power supply and bridge circuit, which is triggered upon projectile impact by a "make" screen with a simple capacitor discharge circuit. The signals from the gages are recorded on a digital oscilloscope. Calibration and data reduction of the stress gage signals are performed using software described by Franz and Lawrence [13]. Both the targets are impacted with 20-mm FSPs at a nominal impact velocity of 1,067 m/s. The stress gage measurements are presented in Figure 4(c). The rise time of the signal without foam is about 1.0 μ s and with foam is about 2.0 μ s. The maximum stress level attained in both the experiments is about 6.25 GPa. The incorporation of 12.7-mm aluminum foam delayed the stress signal about 14.6 μ s to reach the gage location. We have developed a one-dimensional plane-strain finite element model of these experiments (detail of the model described in the following section) and have obtained about an 18.5- μ s delay in the stress-wave arrival with an impact velocity of 500 m/s (Figure 4c). The finite element prediction also shows a two-step rise in stress in the case of target with aluminum foam. The stress waves generated in the experiments are a combination of spherical dilatation, spherical shear, and planar shear wave fronts. However, the plane-strain model only produces planar dilatation and is not an exact model of the experiment. The finite element model predictions capture both the widening in rise time and delay in stress-wave arrival. The experimental and finite element results identified two important characteristics of aluminum foam under stress-wave propagation: (1) aluminum foam increases the rise time of the propagating stress-wave, and (2) incorporation of aluminum-foam introduces a significant delay in stress-wave propagation. In order to determine the effect of aluminum-foam thickness, a second set of experiments is conducted.

The second set of stress-wave experiments deals with two ballistic targets with different aluminum foam thickness (12.7 mm and 30.48 mm) and is shown in Figure 5(a). An additional ceramic matrix composite layer (AS109, particulate SiC in Al₂O₃ matrix with a small amount of aluminum, made by Lanxide Armor Products) is bonded with the target described in Figure 4(b). The nominal impact velocity of a 20-mm FSP was 915 m/s. The projectile impact on the first target (Test # 1, with 12.7-mm aluminum foam) shattered the AS109 ceramic (Figure 5[b]), deformed the HHS plate, and densified the aluminum foam (Figure 5[c]). The stress gage recorded a stress pulse with the maximum stress

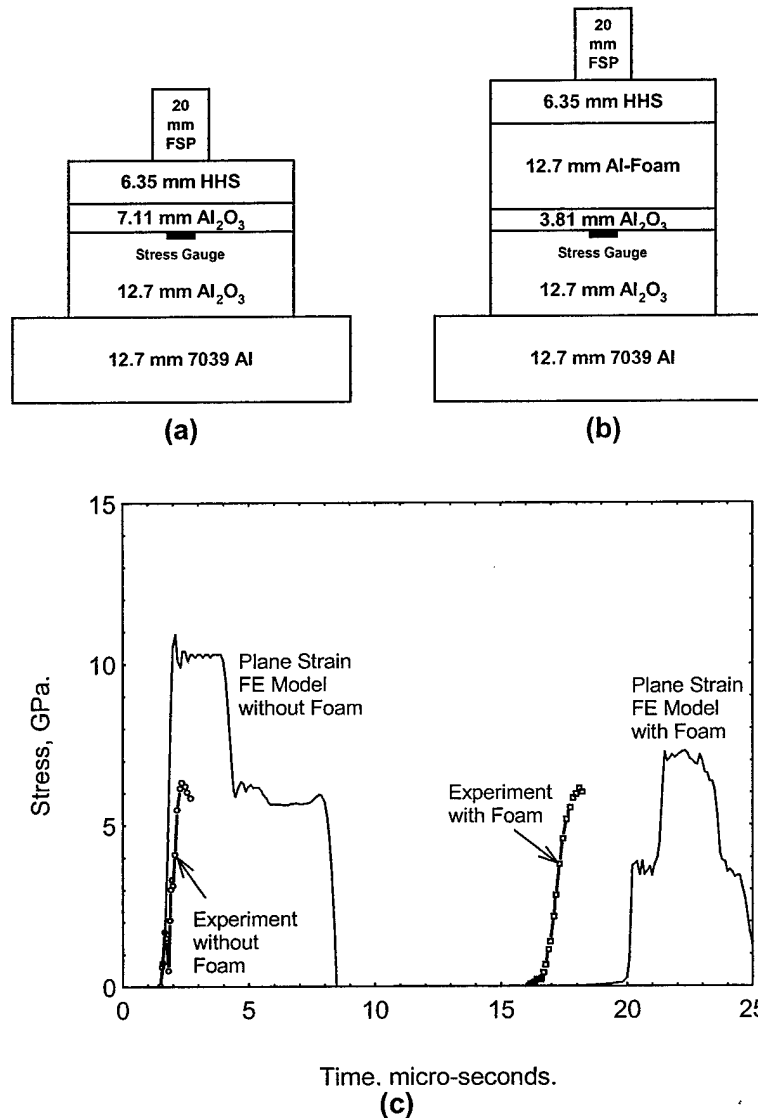
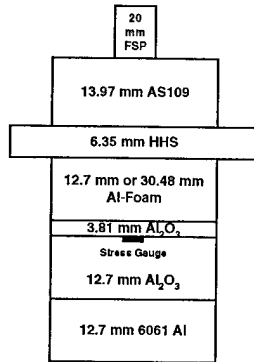
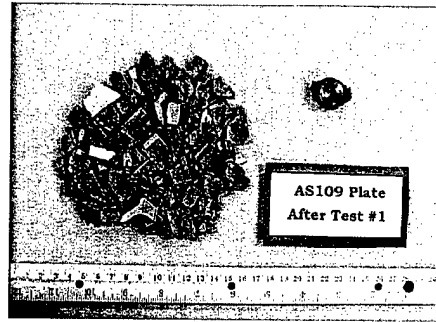


Figure 4. Stress wave experiment with and without aluminum foam (a) target without aluminum foam (b) target with aluminum foam (c) response of the stress gages and plane strain predictions.

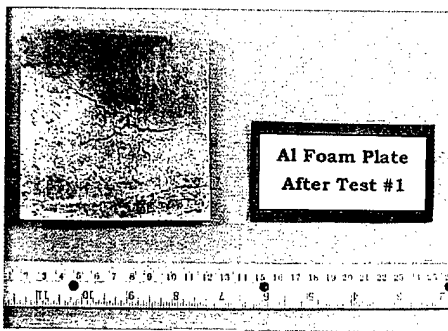
amplitude of about 0.825 GPa. Impact on the second target (Test # 2, with 39.48-mm aluminum foam) showed similar fracture of AS109 ceramic and similar deformation of the HHS plate. However, the aluminum foam is partially densified (cross-section, Figure 5[d]), and the stress gage did not record any signal. The major conclusion from these two experiments is that if the foam is not completely densified across the entire layer thickness, it does not allow any measurable stress waves to pass through. The air/gas-filled cellular structure of the aluminum foam makes the stress-wave propagation difficult. The cell wall



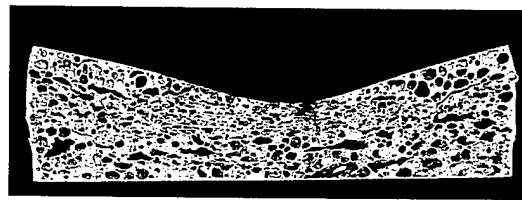
(a)



(b)



(c)



Al Foam Plate
After Test # 2

(d)

Figure 5. Stress wave experiment with different foam thickness (a) target with aluminum foam (b) fracture of AS109 ceramic strike face (c) deformation of aluminum foam after Test #1 (d) cross-section of the deformation of aluminum foam after Test #2.

acts as tiny wave-guide and dispersion of stress waves takes place. The deformation of closed-cell foam occurs by cell-wall buckling and plastic collapse, which leads to localized densification. The deformation and densification originates from the point of applied load and propagates in the direction perpendicular and transverse to the applied load. Effective stress-wave propagation can thus only occur when the closed-cell foam is completely densified. If the stress wave cannot reach the backing plate until the foam is completely densified, then the closed-cell foam has potential to improve the ballistic efficiency of the armor. A detailed finite element analysis of one-dimensional plane-strain stress-wave propagation in multilayer foam integral armor is presented next.

3. Stress Wave Propagation in Aluminum Foam Integral Armor

One-dimensional plane-strain stress-wave propagation in CIA and the effect of nonlinear EPDM rubber-layer thickness has been discussed by Gama et al. [5, 14]. One-dimensional plate impact produces planar dilatational stress-wave propagation in both the projectile and target. On the other hand, the impact of a three-dimensional (3-D) projectile (e.g., FSP) on a multilayer-thick armor plate produces 3-D spherical dilatational, spherical shear, and planar shear wave fronts. Since the dilatational wave speed is higher than the shear wave speed, the through-thickness stress-wave propagation in the impact centerline can be assumed planar, and our analyses are valid only in this region. The through-thickness and impact direction is assumed aligned with the coordinate axis z (3), and the in-plane axes are denoted by x and y (1 and 2). The rubber layer of the integral armor is replaced with an aluminum-foam layer (Figure 6). The individual layers are assumed perfectly bonded to each other. The thickness of the steel impact plate (5 mm), cover layer (2.54 mm), ceramic layer (17.78 mm), and the backing plate (14.15 mm) is kept constant throughout the analyses. The aluminum-foam layer thickness is varied between 12.7 mm and 25.4 mm. This combination of layer thicknesses represents an integral armor of areal density of about 97.65 kg/m² (20 psf). Linear elastic material properties are used to model the impact plate, cover layer, ceramic layer, and the backing plate (Table 1). The aluminum-foam is modeled with the MAT_HONEYCOMB material model within the explicit finite element code LS-DYNA 940, and the properties are extracted for foam density 0.57 gm/cc from Figure 3. The impact velocity of the steel plate is varied between 250 m/s to 750 m/s. The stress-wave propagation in the aluminum-foam armor is compared to armor without foam.

Figure 6 shows the deformation of aluminum-foam layer at different time intervals when impacted at 500 m/s. The plastic collapse and densification of foam starts at the impact side while the rest of the material remains elastic. It takes about 30 μ s for the complete densification of 12.7-mm aluminum foam. The stress-wave propagation in the individual layers is a function of material properties and layer thickness. The dynamic response at midthickness of the individual layers is presented in Figure 7 as a function of time (aluminum-foam thickness = 12.7 mm, impact velocity = 500 m/s). Through-thickness normal stress is made nondimensional by the maximum compressive stress developed in the cover layer. The first compressive pulse in the cover layer is the input to the system. The stress in the cover layer becomes tensile as soon as the projectile bounces back from the target and the rest of the response is the reverberation of

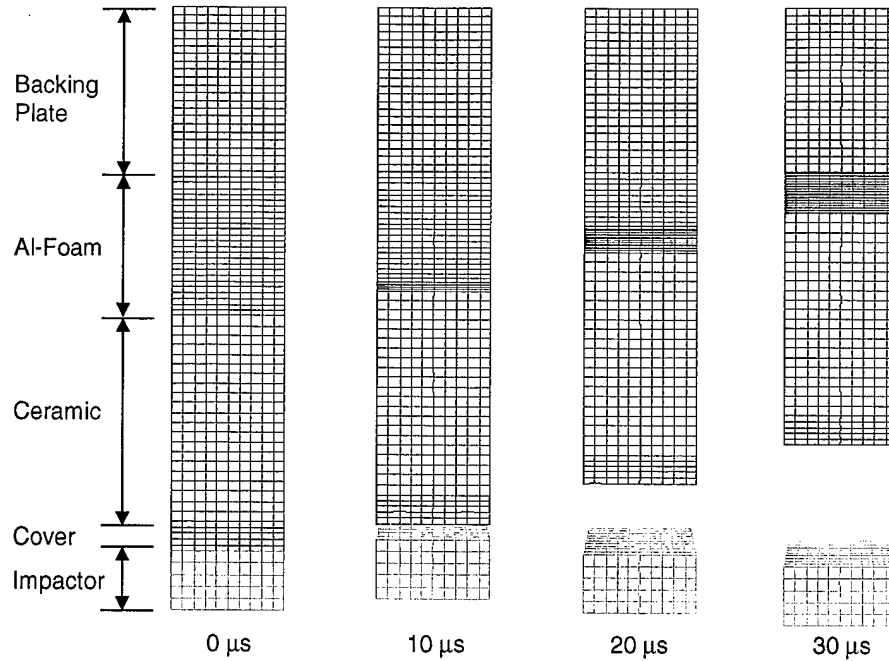


Figure 6. Plane strain finite element model of aluminum-foam integral armor and the dynamic deformation of the aluminum-foam layer.

Table 1. Material properties used in the one-dimensional finite element model.

Material	Young's modulus, E, GPa		Poisson's ratio, ν		Density, ρ , kg/m ³	
Projectile	206.80		0.30		7850	
Cover	8.50		0.28		1783	
Ceramic	310.30		0.25		3500	
Backing Plate	8.50		0.28		1783	
	E, GPa	ρ , kg/m ³	Poisson's ratio of densified foam, $\nu_{\text{densified}}$	Yield stress, σ_y , MPa	Volume fraction of densified foam ν_f , densified	Modulus of densified foam $E_{\text{densified}}$, GPa
Aluminum Foam	0.177	470	0.285	241.40	0.29	68.97

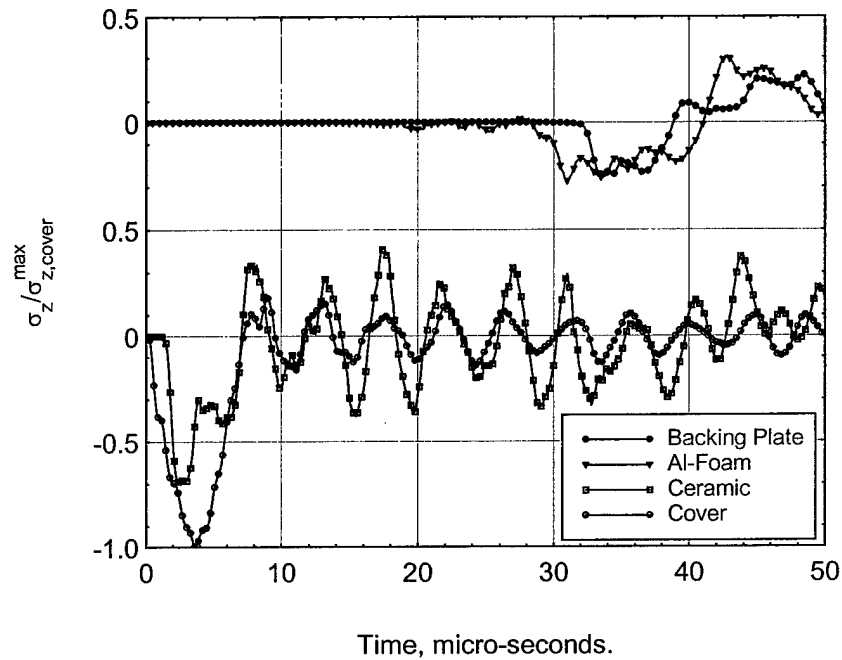


Figure 7. Dynamic response of individual layers, aluminum-foam thickness = 12.7-mm, impact velocity = 500 m/s.

the input pulse and the interaction with the adjacent ceramic layer. The input pulse in the cover layer is transmitted to the ceramic layer through the cover/ceramic interface. The transmission and reflection coefficients can be estimated using one-dimensional wave propagation theory [15]. The response of the aluminum foam layer and the backing plate is presented with a coordinate shift in stress. The transmission and reflection coefficients in the ceramic-foam interface are 0.0173 and -0.9827 respectively, which means that most of the compressive stress pulse will be reflected as tensile stress in the ceramic-foam interface before the collapse of aluminum foam. After the collapse and densification of aluminum foam layer (time > 26 μ s), significant stress rise and propagation is observed in both the aluminum foam and backing plate. The maximum amplitude of the stress pulse transferred into the backing plate is about 25% of the input in the cover layer.

The response of aluminum foam (impact velocity = 500 m/s) as a function of layer thickness, l , is shown in Figure 8. The computation for foam thickness 12.7 mm and 19.1 mm was terminated at 50 μ s and for 25.4 mm at 65 μ s. The peak stresses are almost 25% of the input to the cover layer for all foam thicknesses. The stresses, however, become increasingly oscillatory with increased foam thickness. The arrival time of the stress pulse in the foam layer

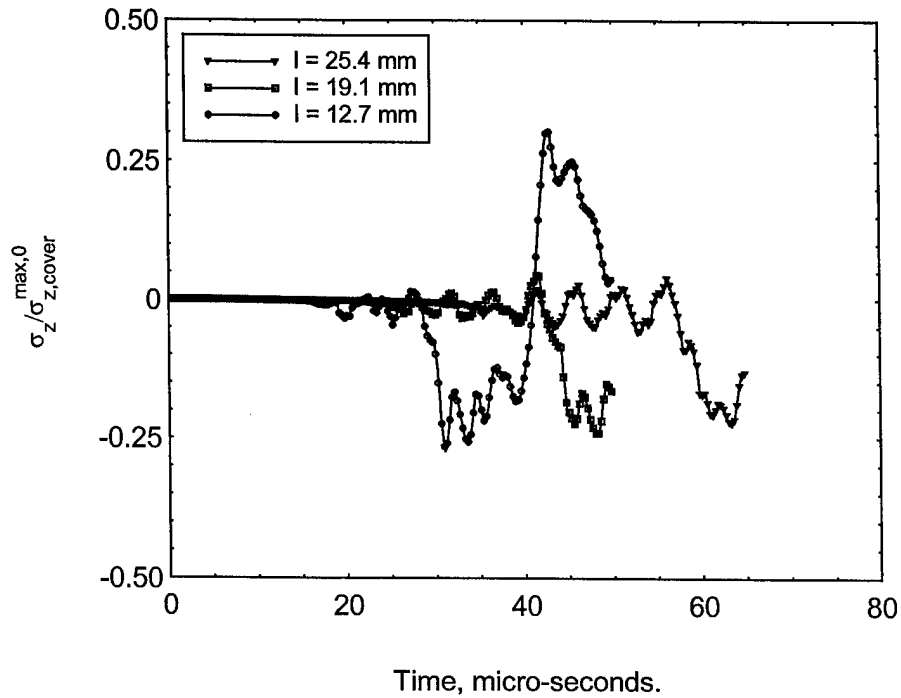
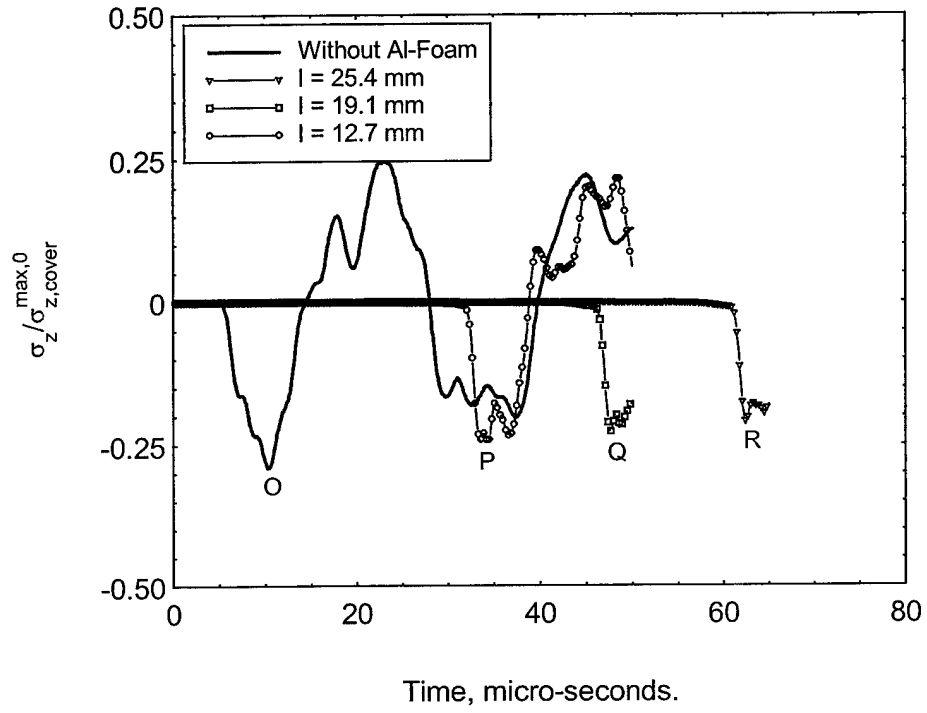
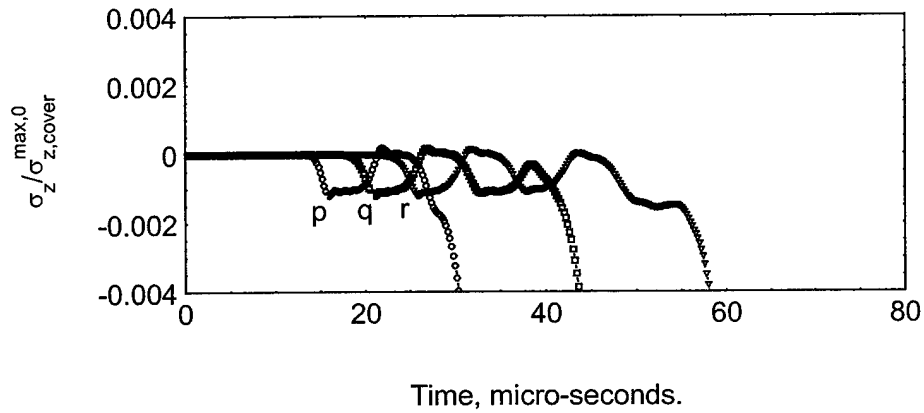


Figure 8. Dynamic response of aluminum-foam layer as a function of foam thickness, impact velocity = 500 m/s.

increases as a direct consequence of increased foam thickness and is related with the stress arrival at the backing plate (Figure 9). The solid line represents the response of backing plate without any foam (Figure 9a). The stress amplitude is found to decrease with the increase in foam thickness. The difference in the time of stress arrival to the backing plate with and without foam is termed as the time delay and increases with foam thickness. The peaks P, Q, and R in Figure 9a represent stress transfer to the backing plate after complete densification of the foam; however, a close-up shows earlier stress pulses (p, q, and r; Figure 9b) before the densification of foam and is termed as elastic stress transfer. The elastic stress transfer is less than 1% of input to the cover for all impact velocities studied (Figure 10). On the other hand, the stress transfer (for impact velocities 500 and 750 m/s) after complete foam densification linearly decreases at a rate of 1.1%/mm of foam thickness. The time delay of stress arrival in the backing plate is presented in Figure 11 and is found to be increasing with foam thickness. The time delay of elastic pulse for all impact velocities is about 0.75 $\mu\text{s}/\text{mm}$; however, the rate of time delay after foam densification decreases as impact velocity increases. These rates of delay are 2.16 and 1.42 $\mu\text{s}/\text{mm}$ for impact velocities 500 and 750 m/s. At impact velocities higher than 750 m/s, the rate of delay approaches the rate of delay of the elastic pulse (0.75 $\mu\text{s}/\text{mm}$).



(a)



(b)

Figure 9. Dynamic response of the backing plate as a function of foam-layer thickness, impact velocity = 500 m/s, (a) effect of foam thickness (b) close-up of the response shows elastic response.

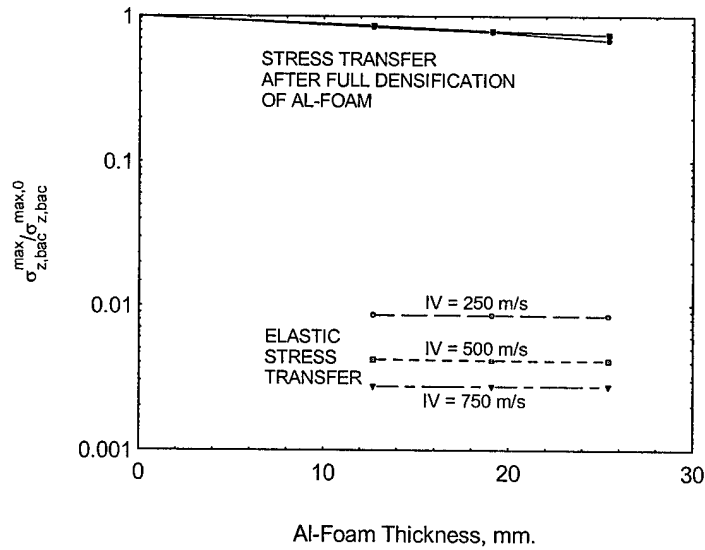


Figure 10. Transmission of stress pulse in the backing plate as a function of foam thickness.

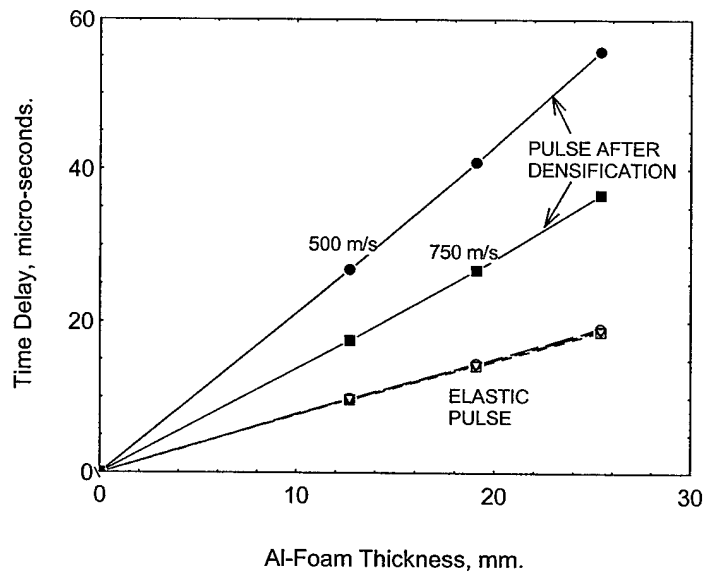


Figure 11. Time delay in the stress-wave arrival at the backing plate as a function of foam thickness.

As stated earlier, the one-dimensional stress analysis is valid at the impact centerline without penetration in the armor. In the real impact event, the penetration event follows the stress-wave propagation and the wave front is

nonplanar. In order to investigate the penetration event, a quarter-symmetric three-dimensional model of aluminum foam integral armor impacted by a 20-mm FSP is developed. The foam layer thickness is taken as 19.1 mm. To mimic the stress-wave experiment done by Yu et al. [11], a thin layer of elastic-plastic material was incorporated in the model between the ceramic and aluminum foam layer. The initial impact velocity of the projectile is set to 900 m/s. The projectile and ceramic is modeled with MAT_PLASTIC_KINEMATIC and the backing plate is modeled with MAT_COMPOSITE_FAILURE_SOLID material models (Table 2). Figure 12 shows the sequence of projectile penetration and dynamic deformation of the aluminum foam. The solution is terminated after 63 μ s because the foam cells are compressed down to infinitesimal thickness, and the time step required for such solution is so small that it takes infinite time to solve the problem. The cross-sectional view of the deformed aluminum foam [11] (Figures 5[d] and 13) shows that the deformation pattern obtained from the numerical simulation matches well with the experimental observation. The deformation pattern of the aluminum-foam also suggests that if an aluminum-foam plate is placed after the backing plate, it could contain the dynamic deflection of the armor.

Table 2. Material properties used in the three-dimensional finite element model.

Material	E, GPa	ν	ρ , kg/m ³	σ_y , MPa	Tangent modulus, E _t , GPa		
FSP	206.91	0.285	7850	1069.1	2.0		
Cover	20.00	0.22	1783	200.0	15.0		
Ceramic	310.30	0.25	3500	3000.0	0.0		
	E, GPa	ρ , kg/m ³	$\nu_{\text{densified}}$	σ_y , MPa	ν_t , densified	E _{densified} , GPa	
Aluminum Foam	0.177	470	0.285	241.40	0.29	68.97	
	ρ , kg/m ³	Modulus, GPa		Poisson's ratio		Shear modulus, GPa	
Backing Plate	1783	E ₁₁	29.48	ν_{21}	0.0085	G ₁₂	3.79
		E ₂₂	29.48	ν_{31}	0.1145	G ₂₃	3.79
		E ₃₃	29.48	ν_{32}	0.1145	G ₃₁	3.79

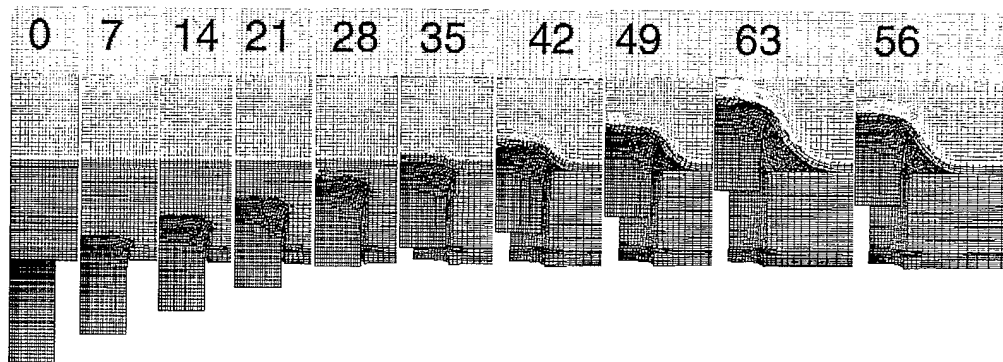


Figure 12. FE solution of dynamic deformation of aluminum-foam integral armor. Numbers indicate time in microseconds.

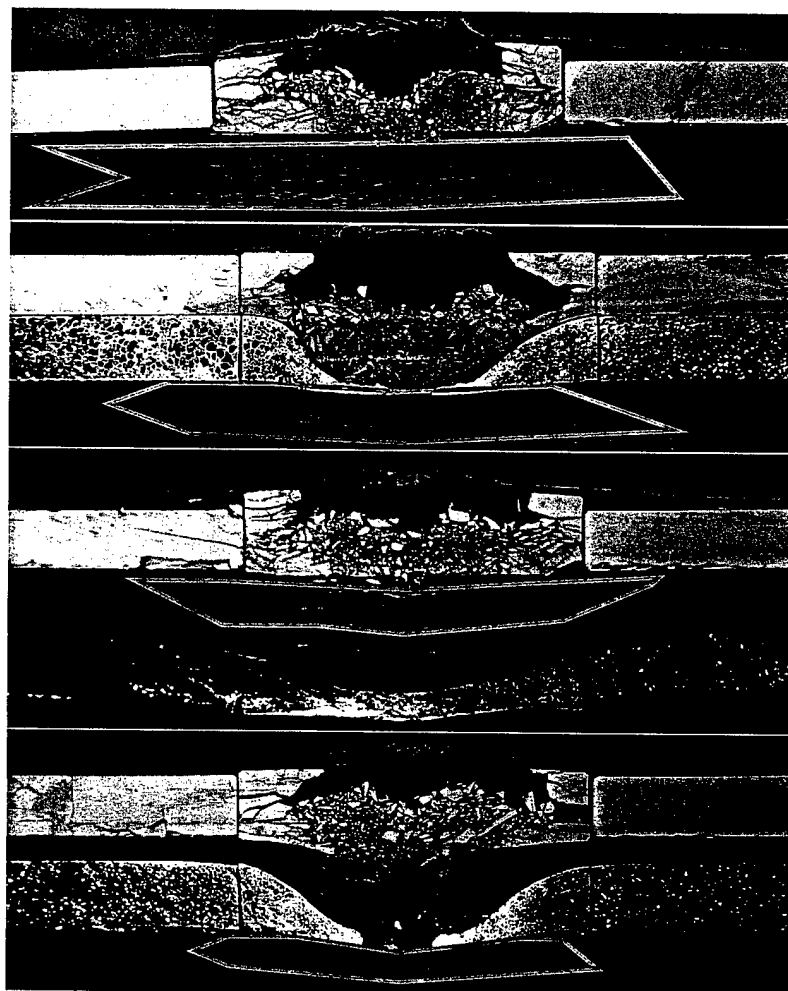


Figure 13. Impact damage modes of the aluminum-foam integral armor.

4. Design of Aluminum Foam Integral Armor

Based on the stress-wave experiment of Yu et al. [11] and the numerical simulation presented in section 3, a test matrix has been developed (Figure 14) to assess the potential benefits of using metal foams in an integral armor and to design the next generation integral armor to satisfy the Army requirements [1]. Three different designs of integral armor with metal foam have been proposed. These designs represent unique functionality of the aluminum foams in the integral armor. The rubber layer of the baseline CIA (Figure 14a, Baseline) has been simply replaced by the aluminum foam (Figure 14b, Design 1) to eliminate any relative rotational degrees of freedom between ceramic and backing plate, to improve structural stiffness of the armor, and to attenuate the stress-wave propagation. The next design (Figure 14c, Design 2) includes an additional aluminum foam backing plate to minimize dynamic deflection. The last design (Figure 14d, Design 3) uses a rubber layer and a thin composite inner layer to distribute the load over a greater region on the metal foam. The material system and individual layer thickness is marked on Figure 14. All designs have the same areal density of 97.65 kg/m² (20 lb/ft²) as the base-line CAV integral armor. The thickness of the cover layer and the ceramic layer is kept constant for all design cases. The foam thickness is also kept constant at 19.00 mm to minimize the production cost of foam panels. If rubber is used in the foam armor panels, the thickness is chosen to be the same as the base line. The only parameter varied to keep the areal density constant is the backing plate thickness.

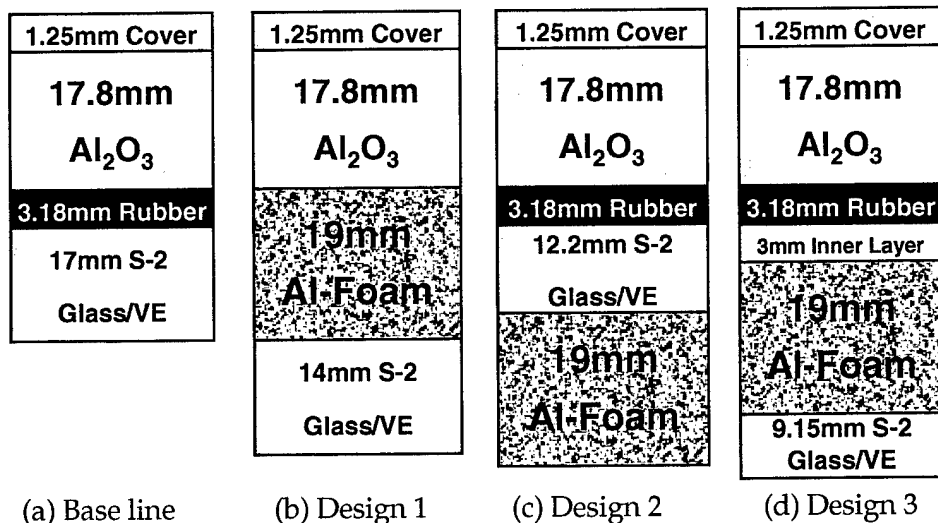


Figure 14. Innovative design of aluminum-foam integral armor.

5. Multistep Processing of Armor Panels

A total of four base-line armor panels and one of each aluminum foam CIA configuration is manufactured using a multistep manufacturing technique. This method is presented in Figure 15. The composite backing plates of different thicknesses are processed using vacuum-assisted resin-transfer molding (VARTM). Details of the VARTM process can be found [16]. Plain weave S-2 glass fabric (24 oz/yd²) with 365-mm sizing is used to make the preforms. The preforms are infused with vinyl ester 411-C50 resin, cured at room temperature and postcured at 121 °C (250 °F) for 3 hr. The S-2 glass/vinyl ester panels are then machined to 305- × 305-mm size. EPDM rubber sheets of the same size are washed with soap and water and dried, and a thin coating of LORD 7701 primer is applied to both sides. Closed-cell aluminum-foam panels of nominal density 500 kg/m³ and of dimension 101.6 × 101.6 × 19.0 mm were fabricated. The foam panels are cleaned with distilled water and dried at room temperature. A solution containing 10% glycidoxy (epoxy) functional methoxy silane (Dow Corning® Z-6040) is prepared with deionized water. Acetic acid is added to the solution to maintain pH in the 3.5–4.0 range. The aluminum foam panels are then soaked into the silane solution and oven dried for an hour at 90 °C. Hexagonal ceramic tiles (AD-90) are cleaned with compressed air. Nonhexagonal ceramic pieces required making a 305- × 305-mm-square array of tiles cut from the hexagonal tiles using a slot grinder. Fishing lines are cut into small pieces and bonded with spray adhesive on the sides of the ceramic tile to ensure a gap between adjacent tiles. The next step is to bond the individual layers with SC-11 epoxy resin. A wooden frame is made to hold all the layers together. A peel ply is used to avoid contact between the wooden mold and the part. The backing plate is first placed on the wooden frame. A thin layer of epoxy resin is then evenly distributed on top. To control the bond-line thickness, a glass scrim cloth (0.125 mm thick) is placed on the backing plate. More resin is added on top of the scrim cloth. The rubber (or aluminum foam) layer is laid next. On top of the rubber layer, resin and scrim cloth are placed to bond the next layer (ceramic layer or any successive layer). Once the hand lay-up of all layers is completed, the assembly is placed in a vacuum bag with sufficient breather material to absorb the excess epoxy resin. The vacuum bag is then placed inside an oven and the part is cured at 121 °C (250 °F) for 2 hr and at 149 °C (300 °F) for another 2 hr under vacuum. Once the cure is complete, the part is slowly cooled in the oven under vacuum. This armor plate is then covered with two layers of S-2 glass fabric and VARTM processed with vinyl ester 411-C50 resin at room temperature to obtain the cover layer. The complete integral armor is then postcured at 121 °C (250 °F) for 3 hr.

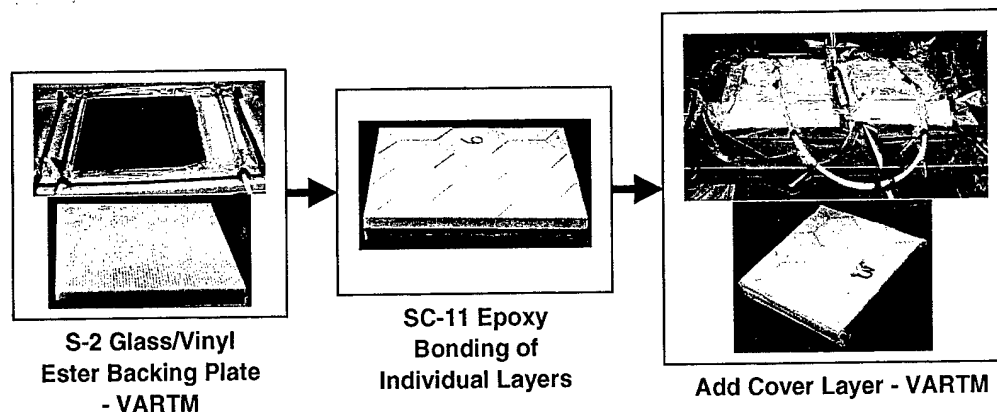


Figure 15. Multistep processing of integral armor.

6. Ballistic Testing of Armor Panels

Integral armor panels are impacted with 20-mm FSP projectiles. Previous research suggested that a 20-mm FSP with impact velocity of 838 m/s (2,750 ft/s) defeats a 97.6 kg/m² (20 lb/ft²) CIA without penetrating the backing plate [3, 4]. Accordingly, all the impact tests were conducted at a nominal impact velocity of 838 m/s.

7. Ballistic Test Results and Discussion

Dynamic deflection of the back face of the armor under incomplete/partial penetration is a critical performance metric [1]. The integral armor panels were mounted on a thick backing of plasticine clay before projectile impact. The dynamic deformation of the back face of the armor is engraved in the plasticine clay after the impact event. This dynamic deflection is then measured as a function of radial location and is presented in Figure 16 for all the tests done. Dynamic deflection of the baseline CIA is presented with the error bars from four test specimens. The curve has a bell shape with a peak at about 32 mm (1.25 in) and a span diameter of about 200 mm (8.0 in). Design 1 has a dynamic deflection contour, which shows less deflection over the whole span as compared to the base line. Design 2 has the least dynamic deflection among all the armor panels tested. Design 3 has higher deflection in the central region but less over the rest of the span as compared to the base line. These observations are correlated with the deformation and damage profile presented in Figure 16.

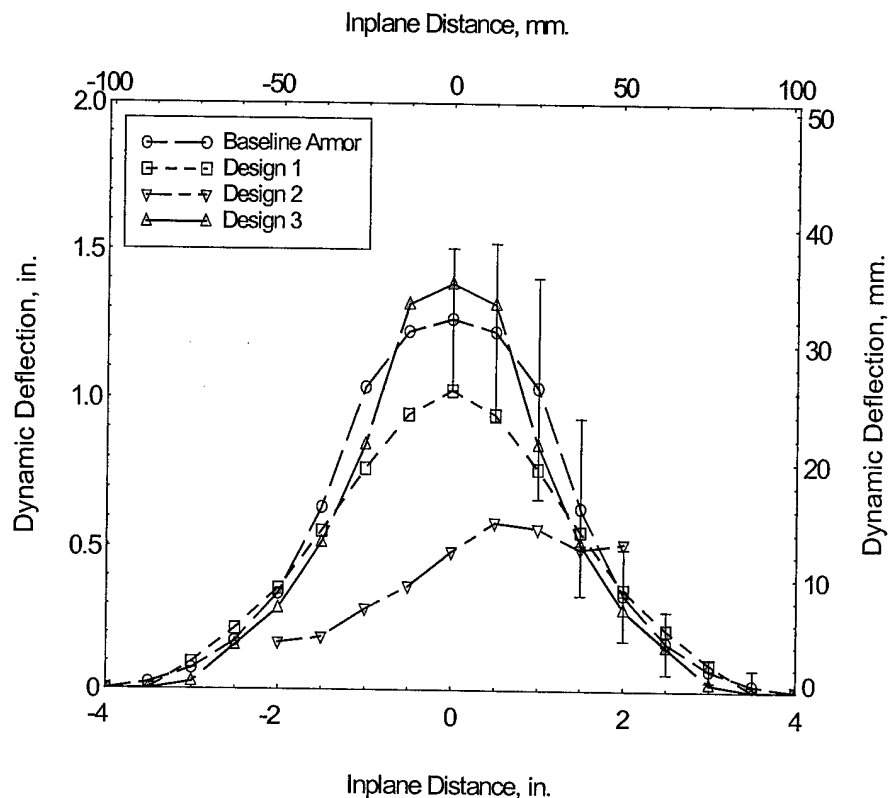


Figure 16. Dynamic deflection of aluminum-foam integral armor.

The armor panels after the ballistic impact is carefully removed from the test fixture such that all the fractured ceramic is contained in the impact cavity other than material ejected during the impact. The impact cavity is then filled with vinyl ester resin to hold the broken ceramic pieces in place. The armor panels are then sectioned, polished, and pictures are taken with a digital camera. These pictures are shown in Figure 16 according to the sequence described in the test matrix and provide us the information on deformation, damage, and relative comparisons between them. The base-line armor shows severe ceramic fracture, cover push-out, penetration through rubber, and the largest volumetric delamination of the backing plate. The load distribution by the fractured ceramic particles on the backing plate during impact is equivalent to one hexagonal tile area. A spring-back effect is observed in all armor panels such that the permanent (static) deformation of the back face is less than 10% of the maximum dynamic deflection.

The overall performance of Design 1 is better than the base line. The volumetric ceramic fracture is less than that of the base line. Most of the ceramic particles are small and medium in size, and almost no pieces are larger than the particles observed in the base line. This pattern of ceramic fracture appears to be superior

and is believed to absorb more kinetic energy of the projectile. Deformation of aluminum foam is of inverted bell shape and is localized. The densification of aluminum foam is localized under the projectile head and in a small surrounding area. Since there is no stress-wave transfer to the backing plate before the complete densification, the aluminum foam is acting as a stress wave filter. The deformation pattern of aluminum foam suggests that the load distribution on the backing plate is on a much smaller area than the base line. The volumetric delamination of the backing plate is also less than the base line, possibly due to a significant decrease in premature damage due to stress wave propagation before the arrival of the projectile. It was demonstrated earlier (Figure 15) that the dynamic deflection of Design 1 is less than the base line suggesting that the residual kinetic energy of the projectile pushing the backing plate is less than that of the base line. Design 1 is thus proven to be a better armor solution than the base-line CIA solution with a rubber layer.

The comparison between the Design 2 and the base line is easier if Design 2 is considered the same as the base line with added aluminum-foam backing. The deformation pattern of the cover, ceramic, and rubber layer is similar to the base line. However, the volumetric delamination of the backing plate is less than the base line and is comparable to Design 1. The deformation pattern of the aluminum-foam-backing plate at the composite backing/aluminum-foam interface is a representation of the dynamic deformation of the composite back face. The deformation of aluminum foam is mostly plastic. The dynamic deformation presented in Figure 15 is the deflection of the back face of the aluminum foam, which we can see from Figure 16 as a permanent deformation. The damage in the aluminum-foam-backing plate is distributed over the whole span of the armor plate.

In Design 3, the composite inner layer served the purpose of distributing the load over the aluminum foam. The ceramic fracture is similar to the base line, and this consideration does not yield the benefit of Design 1. Even though the volumetric delamination is least compared to all designs, its dynamic deflection improved only slightly over the base-line CIA.

8. Summary

The unique capability of closed-cell aluminum foam in delaying stress-wave propagation and attenuation is presented through experimental and numerical analyses. It has been found that the dynamic deformation of aluminum foam starts at the impact face and propagates through the thickness till complete densification. The cellular structure makes elastic stress-wave propagation difficult. Effective stress-wave propagation through aluminum foam only occurs

after complete densification. If the foam densification is partial, it can act as a stress wave filter. The time required for complete densification appears as a time delay in stress transfer to the next layer (backing plate) and is found to be a linear function of foam thickness. Aluminum foam is also found to reduce the amplitude of the stress pulse transferred to the backing plate. Based on the experimental and numerical stress-wave propagation results, three novel, aluminum-foam, integral armor designs have been evaluated.

Various CIA panels have been ballistically tested under 20-mm FSP impact to assess the associated damage of base-line and aluminum-foam integral armor. The relative study between three different aluminum foam armor designs and their comparison with the base line gives insight into the performance and deformation behavior of this new class of aluminum-foam-based CIA. In comparison to the base line, Design 1 performed the best by providing better ceramic fracture, less cover separation, localized aluminum-foam deformation, less dynamic deflection, and less volumetric delamination of the backing plate. The superior performance of this novel, aluminum-foam, integral armor is a step forward to lighter and more damage-tolerant CIA for the next generation of armored vehicles.

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13. ABSTRACT (Maximum 200 words) Closed-cell aluminum foam offers a unique combination of properties such as low density, high stiffness, strength, and energy absorption that can be tailored through design of the microstructure. During ballistic impact, the foam exhibits significant nonlinear deformation and stress-wave attenuation. Composite structural armor panels containing closed-cell aluminum foam are impacted with 20-mm fragment-simulating projectiles (FSP). One-dimensional plane strain finite element analysis (FEA) of stress-wave propagation is performed to understand the dynamic response and deformation mechanisms. The FEA results correlate well with the experimental observation that aluminum foam can delay and attenuate stress waves. It is identified that the aluminum foam transmits an insignificant amount of stress pulse before complete densification. The ballistic performance of aluminum foam-based composite integral armor is compared with the base-line integral armor of equivalent areal density by impacting panels with 20-mm FSP. A comparative damage study reveals that the aluminum-foam armor has better and finer ceramic fracture and less volumetric delamination of the composite backing plate as compared to the base line. The aluminum-foam armors also showed less dynamic deflection of the backing plate than the base line. These attributes of the aluminum foam in integral armor system add a new dimension in the design of lightweight armor for the future armored vehicles.				
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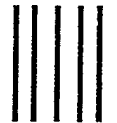
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